QCD spin physics: status, and prospects for RHIC[*]

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Abstract. We review some of the recent developments in QCD spin physics and highlight the spin program now underway at RHIC.

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1. Introduction

For many years now, spin has played a very prominent role in QCD. The field of QCD spin physics has been carried by the hugely successful experimental program of polarized deeply-inelastic lepton-nucleon scattering (DIS), and by a simultaneous tremendous progress in theory. This talk summarizes some of the interesting new developments in the past roughly two years. As we will see, there have yet again been exciting new data from polarized lepton-nucleon scattering, but also from the world's first polarized pp collider, RHIC. There have been very significant advances in theory as well. It will not be possible to cover all developments. I will select those topics that may be of greatest interest to the attendees of a high-energy physics phenomenology conference.

2. Nucleon helicity structure

2.1 What we have learned so far

Until a few years ago, polarized inclusive DIS played the dominant role in QCD spin physics [1]. At the center of attention was the nucleon's spin structure function $g_1(x, Q^2)$. Fig. 1 shows a recent compilation [2] of the world data on $g_1(x, Q^2)$. These data have provided much interesting information about the nucleon and QCD. For example, they have given direct access to the helicity-dependent parton distribution functions of the nucleon,

$$\Delta f(x, Q^2) = f^+ - f^- \qquad (f = q, \bar{q}, g) , \tag{1}$$

which count the numbers of partons with same helicity as the nucleon, minus opposite. Polarized DIS actually measures the combinations $\Delta q + \Delta \bar{q}$. From $x \to 0$ extrapolation

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of the structure functions for proton and neutron targets it has been possible to test and confirm the Bjorken sum rule [3]. Polarized DIS data, when combined with input from hadronic β decays, have allowed to extract the – unexpectedly small – nucleon's axial charge $\sim \langle P|\bar{\psi}\,\gamma^\mu\,\gamma^5\,\psi|P\rangle$, which is identified with the quark spin contribution to the nucleon spin [1].
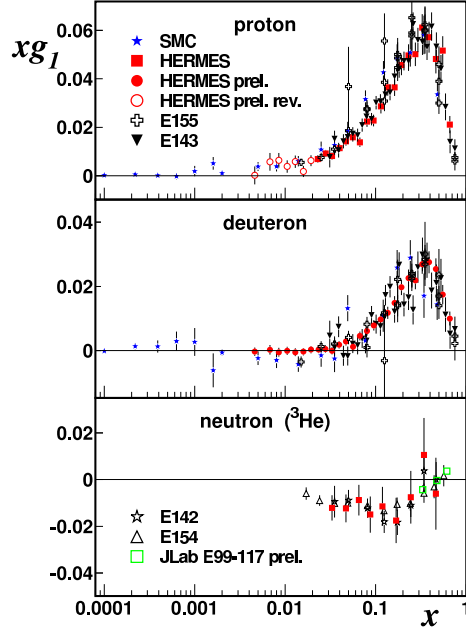

Figure 1. Data on the spin structure function g_1, as compiled and shown in [2].

2.2 Things we would like to know

The results from polarized inclusive DIS have also led us to identify the next important goals in our quest for understanding the spin structure of the nucleon. The measurement of gluon polarization $\Delta g = g^+ - g^-$ rightly is a main emphasis at several experiments in spin physics today, since Δg could be a major contributor to the nucleon spin. Also, more detailed understanding of polarized quark distributions is clearly needed; for example, we would like to know about flavor symmetry breakings in the polarized nucleon sea, details about strange quark polarization, the relations to the F, D values extracted from baryon β decays, and also about the small-x and large-x behavior of the densities. Again, these questions are being addressed by current experiments. Finally, we would like to find out how much orbital angular momentum quarks and gluons contribute to the nucleon spin. Ji showed [4] that their total angular momenta may be extracted from deeply-virtual Compton scattering, which has sparked much experimental activity also in this area.

2.3 Current experiments in high-energy spin physics

There are several fixed-target lepton-nucleon scattering experiments around the world with dedicated spin physics programs. I will mention those that play a role in this talk: HERMES at DESY uses HERA's 27.5 GeV polarized electron beam on polarized targets. They have recently completed a run with a transversely polarized target. Semi-inclusive DIS (SIDIS) measurements are one particular strength of HERMES. COMPASS at CERN uses a 160 GeV polarized muon beam. A major emphasis is measuring gluon polarization. There is also a very large spin program at Jefferson Lab, involving several experiments. Large-x structure functions and the DVCS reaction are just two of many objectives there. For the more distant future, there are plans to develop a polarized electron-proton *collider* at BNL, eRHIC [5].

A new milestone has been reached by the advent of the first polarized proton-proton collider, RHIC at BNL. Two physics runs with polarized protons colliding at $\sqrt{s} = 200$ GeV have been completed, and exciting results are emerging. We will see examples in this talk. All components crucial for the initial phase of the spin program with beam polarization up to 50% are in place [6]. This is true for the accelerator (polarized source, Siberian snakes, polarimetry by proton-Carbon and by pp elastic scattering off a jet target) as well as for the detectors. RHIC presently brings to collision 55 bunches with a polarization pattern $\ldots + + - - + + \ldots$ in one ring and $\ldots + - + - + - \ldots$ in the other, which amounts to collisions with different spin combinations every 212 nsec. Polarization has been maintained with a lifetime of about 10 hours. There is still need for improvements in polarization and luminosity for future runs. The two larger RHIC experiments, PHENIX and STAR, have dedicated spin programs focusing on precise measurements of Δg, quark polarizations by flavor, transverse-spin phenomena, and others. A smaller experiment, BRAHMS, investigates single-spin asymmetries. The pp2pp experiment studies elastic pp scattering.

2.4 Accessing gluon polarization Δg

As mentioned above, the measurement of Δg is a main goal of several experiments. The gluon density affects the Q^2-evolution of the structure function $g_1(x, Q^2)$, but the limited lever arm in Q^2 available so far has left Δg virtually unconstrained [7–9]. One way to access Δg in lepton-nucleon scattering is therefore to look at a less inclusive final state that is particularly sensitive to gluons in the initial state. One channel, to be investigated by COMPASS in particular [10], is heavy-flavor production via the photon-gluon fusion process An alternative reaction is $ep \rightarrow h^+ h^- X$, where the two hadrons in the final state have large transverse momentum [10,11].

RHIC will likely dominate the measurements of Δg. Several different processes will be investigated [12] that are sensitive to gluon polarization: high-$p_\perp$ prompt photons $pp \rightarrow \gamma X$, jet or hadron production $pp \rightarrow \mathrm{jet} X$, $pp \rightarrow hX$, and heavy-flavor production $pp \rightarrow (Q\bar{Q})X$. In addition, besides the current $\sqrt{s} = 200$ GeV, also $\sqrt{s} = 500$ GeV will be available at a later stage. All this will allow to determine $\Delta g(x, Q^2)$ in various regions of x, and at different scales. One can compare the Δg extracted in the various channels, and hence check its universality implied by factorization theorems. The latter state that cross sections at high $p_\perp$ (which implies large momentum transfer) may be factorized into universal (process-independent) long-distance pieces that contain the desired information on the (spin) structure of the nucleon, and short-distance parts that describe

the hard interactions of the partons and are amenable to QCD perturbation theory (pQCD). For example, for the reaction $pp \to \pi X$ one has:

$$d\Delta\sigma^{\pi} = \sum_{a,b,c} \Delta a \otimes \Delta b \otimes d\Delta\hat{\sigma}^{c}_{ab} \otimes D^{\pi}_{c} , \qquad (2)$$

where $\otimes$ denotes a convolution and where the sum is over all contributing partonic channels $a + b \to c + X$, with $d\Delta\hat{\sigma}^{c}_{ab}$ the associated spin-dependent partonic cross section. The $\Delta a, \Delta b$ $(a, b = q, \bar{q}, g)$ are the polarized parton densities, and the transition of parton c into the observed π^0 is described by the (spin-independent) fragmentation function D^{π}_{c}. We emphasize that all tools are in place now for treating the spin reactions relevant at RHIC to next-to-leading order (NLO) pQCD [13–16]. NLO corrections significantly improve the theoretical framework; it is known from experience with the unpolarized case that the corrections are indispensable in order to arrive at quantitative predictions for hadronic cross sections. For instance, the dependence on factorization and renormalization scales in the calculation is much reduced when going to NLO. Therefore, only with knowledge of the NLO corrections will one be able to extract Δg reliably. Figure 2 shows NLO predictions [13] for the double-longitudinal spin asymmetry $A_{\mathrm{LL}} = d\Delta\sigma/d\sigma$ for the reaction $pp \to \pi X$ at RHIC, using various different currently allowed parameterizations [7] of $\Delta g(x, Q^2)$. It also shows the statistical errors bars expected for a measurement by PHENIX under the rather conservative assumptions of 40% beam polarizations and 3/pb integrated luminosity. Such numbers are targeted for the early RHIC runs. Recently, first results for A_{LL} in $pp \to \pi X$ have indeed been reported by PHENIX [17], albeit obtained with lower polarization and luminosity. The results are shown in Fig. 3, along with the theoretical predictions that were already displayed in Fig. 2. Interestingly, the data are consistent with a significant (up to a few per cent) negative asymmetry in the region $p_{\perp} \sim 1 \div 4$ GeV, contrary to all predictions shown in the figure. Even though the experimental uncertainties are still large
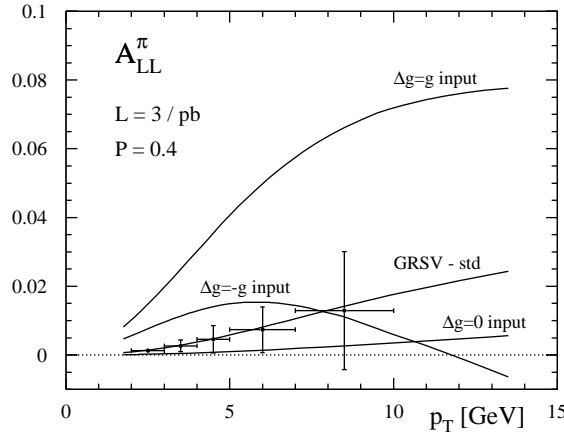

Figure 2. NLO predictions [13] for the spin asymmetry in $pp \to \pi X$ at RHIC, for various Δg. The "error bars" are projections of the uncertainties that can be reached with 40% beam polarizations and 3/pb integrated luminosity.

4

and leave room for a different behavior of A_{LL}^{π}, the new data give motivation to entertain the unexpected possibility of A_{LL}^{π} being negative. As it turns out [18], within pQCD at leading power, there is a lower bound on the asymmetry of about -10^{-3}.

To demonstrate this, we consider the LO cross section integrated over all pion rapidities η and take Mellin moments in $x_T^2 = 4p_\perp^2/S$ of the cross section Eq. (2):

$$\Delta\sigma^{\pi}(N) \equiv \int_0^1 dx_T^2 \left(x_T^2\right)^{N-1} \frac{p_\perp^3 d\Delta\sigma^{\pi}}{dp_\perp} \ . \tag{3}$$

One finds:

$$\Delta\sigma^{\pi}(N) = \sum_{a,b,c} \Delta a^{N+1} \, \Delta b^{N+1} \, \Delta\hat{\sigma}_{ab}^{c,N} \, D_c^{\pi,2N+3} \ , \tag{4}$$

where the $\Delta\hat{\sigma}_{ab}^{c,N}$ are the $\hat{x}_T^2$-moments of the partonic cross sections and, as usual, $f^N \equiv \int_0^1 dx \, x^{N-1} f(x)$ for the parton distribution and fragmentation functions. Explicitly, the dependence on the moments Δg^N of the polarized gluon density is

$$\Delta\sigma^{\pi}(N) = \left(\Delta g^{N+1}\right)^2 \mathcal{A}^N + 2\Delta g^{N+1}\mathcal{B}^N + \mathcal{C}^N \ . \tag{5}$$

Here, $\mathcal{A}^N$ represents the contributions from $gg \to gg$ and $gg \to q\bar{q}$, $\mathcal{B}^N$ the ones from $qg \to qg$, and $\mathcal{C}^N$ those from the (anti)quark scatterings.

Being a quadratic form in Δg^{N+1}, $\Delta\sigma^{\pi}(N)$ possesses an extremum, given by the condition [18]

$$\mathcal{A}^N \Delta g^{N+1} = -\mathcal{B}^N \ . \tag{6}$$

The coefficient $\mathcal{A}^N$ is positive, and Eq. (6) describes a minimum of $\Delta\sigma^{\pi}(N)$, with value
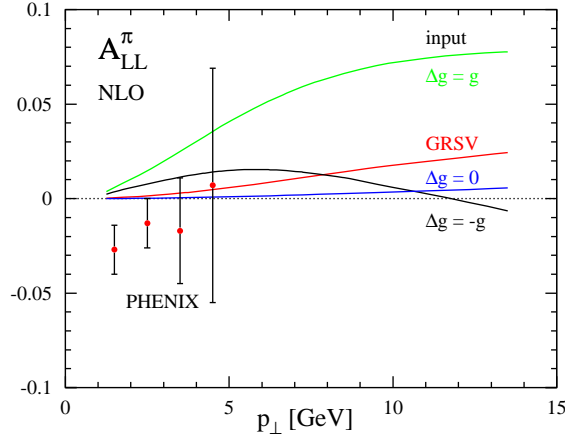

Figure 3. PHENIX data [17] for the spin asymmetry A_{LL}^{π}, along with the NLO predictions from the previous figure.

$$\Delta\sigma^\pi(N)\Big|_{\mathrm{min}} = -\left(\mathcal{B}^N\right)^2 / \mathcal{A}^N + \mathcal{C}^N . \tag{7}$$

It is then straightforward to perform a numerical Mellin inversion of this minimal cross section. The minimal asymmetry resulting from this exercise is negative indeed, but very small: in the range $p_\perp \sim 1 \div 4$ GeV its absolute value does not exceed 10^{-3}. The Δg in Eq. (6) that minimizes the asymmetry has a node and is small, except at large x [18].

Even though some approximations have been made in deriving the bound in Eq. (7), it does exhibit the basic difficulty with a sizable negative A^π_{LL} at moderate $p_\perp$: the fact that the cross section is a quadratic form in Δg effectively means that it is bounded from below. Effects like NLO corrections, choice of scales, and realistic range of rapidity may be thoroughly addressed in a "global" NLO analysis of the data, taking into account the results from polarized DIS as well. Such an analysis has been performed in [18], and it confirms the findings of the simple example above.

What should one conclude if future, more precise, data will indeed confirm a sizable negative A^π_{LL}? Corrections to Eq. (2) as such are down by inverse powers of $1/p_\perp$. Since $p_\perp$ is not too large, such power-suppressed contributions might well be significant. On the other hand, comparisons of unpolarized π^0 spectra measured at RHIC with NLO QCD calculations do not exhibit any compelling trace of non-leading power effects even down to fairly low $p_\perp \gtrsim 1$ GeV, within the uncertainties of the calculation. This is shown in Fig. 4. Clearly, such results provide confidence that the theoretical hard scattering frame-
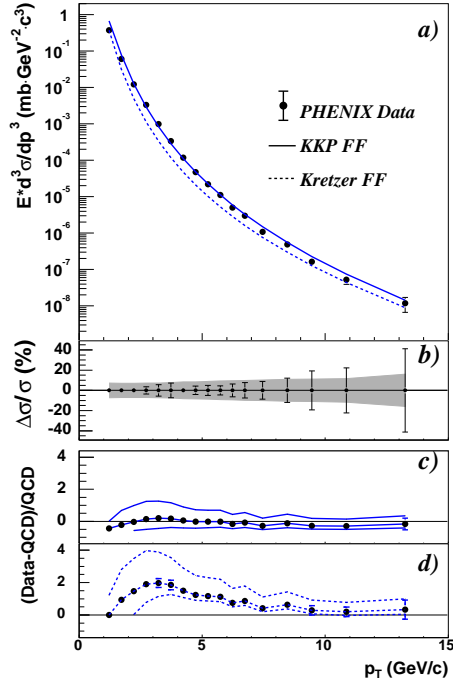

Figure 4. PHENIX data [19] for the unpolarized $pp \to \pi^0 X$ cross section at RHIC, compared to NLO calculations [13]. The plot has been taken from [19].

work used for Figs. 2,3 is indeed adequate. It is conceivable that the spin-dependent cross section with its fairly tedious cancelations has larger power-suppressed contributions than the unpolarized one.

2.5 Further information on quark polarizations

As mentioned earlier, inclusive DIS via photon exchange only gives access to the combinations $\Delta q + \Delta\bar{q}$. There are at least two ways to distinguish between quark and antiquark polarizations, and also to achieve a flavor separation. Semi-inclusive measurements in DIS are one possibility, explored by SMC [20] and, more recently and with higher precision, by HERMES [21]. One detects a hadron in the final state, so that instead of $\Delta q + \Delta\bar{q}$ the polarized DIS cross section becomes sensitive to $\Delta q(x)\, D_q^h(z) + \Delta\bar{q}(x)\, D_{\bar{q}}^h(z)$, for a given quark flavor. Here, the $D_i^h(z)$ are fragmentation functions, with $z = E^h/\nu$. Fig. 5 shows the latest results on the flavor separation by HERMES [21], obtained from their LO Monte-Carlo code based "purity" analysis. Within the still fairly large uncertainties, they are not inconsistent with the large negative polarization of $\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s}$ in the sea that has been implemented in many determinations of polarized parton distributions from inclusive DIS data [7,8] (see curves in Fig. 5). On the other hand, there is no evidence either for a large negative strange quark polarization. For the region $0.023 < x < 0.3$, the extracted Δs integrates [21] to the value $+0.03 \pm 0.03\,(\text{stat.}) \pm 0.01\,(\text{sys.})$, while analyses
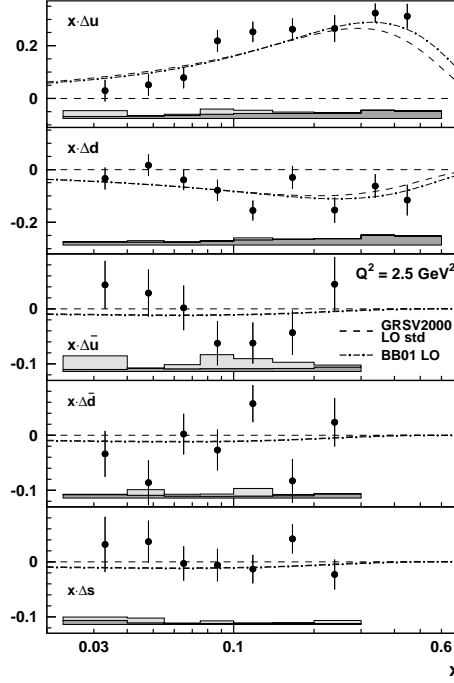

Figure 5. Recent HERMES results [21] for the quark and antiquark polarizations extracted from semi-inclusive DIS.

of inclusive DIS typically prefer an integral of about -0.025. There is much theory activity currently on SIDIS, focusing also on possible systematic improvements to the analysis method employed in [21], among them NLO corrections, target fragmentation, and higher twist contributions [22]. At RHIC [23] one will use $W^{\pm}$ production to determine $\Delta q, \Delta \bar{q}$, making use of parity-violation. Figure 6 shows the expected precision with which it will be possible to determine the light quark and antiquark polarizations. Comparisons of such data taken at much higher scales with those from SIDIS will be extremely interesting.
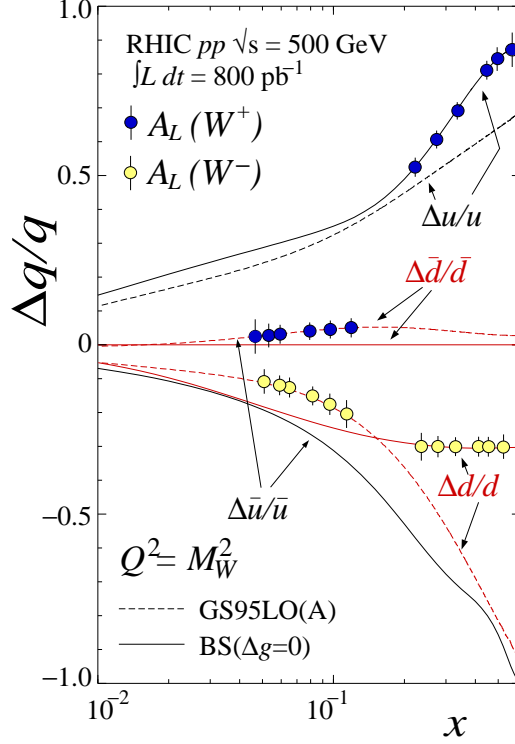

Figure 6. Expected sensitivity [12,23] for the flavor decomposition of quark and anti-quark polarizations at RHIC.

New interesting information on the polarized quark densities has also recently been obtained at high x. The Hall A collaboration at JLab has published their data for the neutron asymmetry A_1^n [24], shown in Fig. 7. The new data points show a clear trend for A_1^n to turn positive at large x. Such data are valuable because the valence region is a particularly useful testing ground for models of nucleon structure. Fig. 7 also shows the extracted valence polarization asymmetries. The data are consistent with constituent quark models [25] predicting $\Delta d/d \to -1/3$ at large x, while "hadron helicity conservation" predictions based on perturbative QCD and the neglect of quark orbital angular momentum [26] give $\Delta d/d \to 1$ and tend to deviate from the data, unless the convergence to 1 sets in very late.
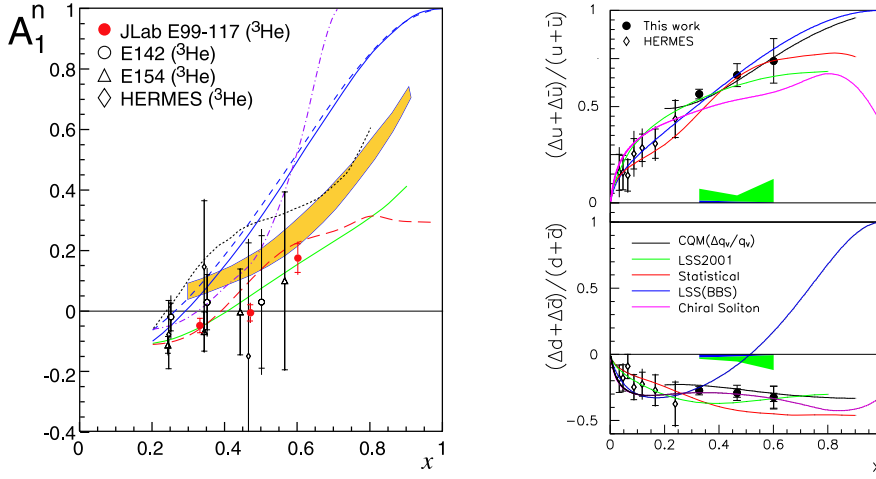
Figure 7. Left: Recent data on A_1^n from the E99-117 experiment [24]. Right: extracted polarization asymmetries for $u + \bar{u}$ and $d + \bar{d}$. For more details and references on the various model predictions, see [24].

3. Transverse-spin phenomena

3.1 Transversity

Besides the unpolarized and the helicity-dependent densities, there is a third set of twist-2 parton distributions, transversity [27]. In analogy with Eq. (1) they measure the net number (parallel minus antiparallel) of partons with transverse polarization in a transversely polarized nucleon:

$$\delta f(x, Q^2) = f^{\uparrow} - f^{\downarrow} \ . \tag{8}$$

In a helicity basis, one finds [27] that transversity corresponds to a helicity-flip structure, as shown in Fig. 8. This precludes a gluon transversity distribution at leading twist. It also makes transversity a probe of chiral symmetry breaking in QCD [28]: perturbative-QCD interactions preserve chirality, and so the helicity flip required to make transversity non-zero must primarily come from soft non-perturbative interactions for which chiral symmetry is broken [28].
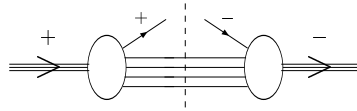

Figure 8. Transversity in helicity basis.

Measurements of transversity are not straightforward. Again the fact that perturbative interactions in the Standard Model do not change chirality (or, for massless quarks, helici-

9

ty) means that inclusive DIS is not useful. Collins, however, showed [29] that properties of fragmentation might be exploited to obtain a "transversity polarimeter": a pion produced in fragmentation will have some transverse momentum with respect to the momentum of the transversely polarized fragmenting parent quark. There may then be a correlation of the form $i\vec{S}_T \cdot (\vec{P}_\pi \times \vec{k}_\perp)$. The fragmentation function associated with this correlation is the Collins function. The phase is required by time-reversal invariance. The situation is depicted in Fig. 9. The Collins function would make a *leading-power* [29] contribution to
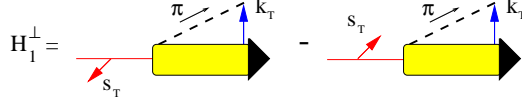

Figure 9. The Collins function.

the single-spin asymmetry $A_\perp$ in the reaction $ep^\uparrow \to e\pi X$:

$$A_\perp \propto |\vec{S}_T| \sin(\phi + \phi_S) \sum_q e_q^2 \delta q(x) H_1^{\perp,q}(z) \, , \tag{9}$$

where ϕ (ϕ_S) is the angle between the lepton plane and the $(\gamma^*\pi)$ plane (and the transverse target spin). We note that very recently a proof for the factorization formula for SIDIS at small transverse momentum was presented [30]. As is evident from Eq. (9), the asymmetry would allow access to transversity if the Collins functions are non-vanishing. A few years ago, HERMES measured the asymmetry for a longitudinally polarized target [31]. For finite Q, the target spin then has a transverse component $\propto M/Q$ relative to the direction of the virtual photon, and the effect may still be there, even though it is now only one of several "higher twist" contributions [32].

3.2 The Sivers function

If "intrinsic" transverse momentum in the fragmentation process plays a crucial role in the asymmetry for $ep^\uparrow \to e\pi X$, a natural question is whether $k_\perp$ in the initial state can be relevant as well. Sivers suggested [33] that the $k_\perp$ distribution of a quark in a transversely polarized hadron could have an azimuthal asymmetry, $\vec{S}_T \cdot (\vec{P} \times \vec{k}_\perp)$, as shown in Fig. 10. There is a qualitative difference between the Collins and Sivers functions, however. While phases will always arise in strong interaction final-state fragmentation, one does not expect them from initial (stable) hadrons, and the Sivers function appears to be ruled out by time-reversal invariance of QCD [29]. Until recently, it was therefore widely believed that origins of single-spin asymmetries as in $ep^\uparrow \to e\pi X$ and other reactions were more likely to be found in final-state fragmentation effects than in initial state parton distributions. However, then came a model calculation [34] that found a leading-power asymmetry in $ep^\uparrow \to e\pi X$ not associated with the Collins effect. It was subsequently realized [35–37] that the calculation of [34] could also be regarded as a model for the Sivers effect. It turned out that the original time-reversal argument against the Sivers function is invalidated by the presence of the Wilson lines in the operators defining the parton density. These are
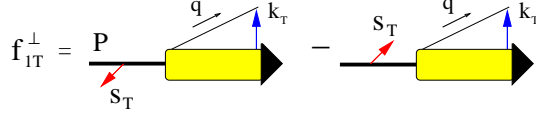
Figure 10. The Sivers function.

required by gauge invariance and had been neglected in [29]. Under time reversal, however, future-pointing Wilson lines turn into past-pointing ones, which changes the time reversal properties of the Sivers function and allows it to be non-vanishing. Now, for a "standard", $k_\perp$-integrated, parton density the gauge link contribution is unity in the $A^+ = 0$ gauge, so one may wonder how it can be relevant for the Sivers function. The point, however, is that for the case of $k_\perp$-dependent parton densities, a gauge link survives even in the light-cone gauge, in a transverse direction at light-cone component $\xi^- = \infty$ [36,37]. Thus, time reversal indeed does not imply that the Sivers function vanishes. The same is true for a function describing transversity in an unpolarized hadron [38]. It is intriguing that these new results are based entirely on the Wilson lines in QCD. Another aspect to the physics importance of the Sivers function is the fact that it arises as an interference of wave functions with angular momenta $J_z = \pm 1/2$ and hence contains information on parton orbital angular momentum [34,39].

3.3 Implications for phenomenology

If the Sivers function is non-vanishing, it will for example make a leading-power contribution to $ep^\uparrow \to e\pi X$, of the form

$$A_\perp \propto |\vec{S}_T| \sin(\phi - \phi_S) \sum_q e_q^2 \, f_{1T}^{\perp;q}(x) \, D_q^\pi(z) \,. \tag{10}$$

This is in competition with the Collins function contribution, Eq. (9); however, the azimuthal angular dependence is discernibly different. HERMES has recently completed an analysis of their data obtained in a run with transverse target polarization, and preliminary results have been presented, indicating contributions from both the Collins and the Sivers effects [40]. A detailed study [41] suggests the surprising feature that the flavor-non-favored Collins functions appear to be equally important as the favored ones. COMPASS, on the other hand, recently reported results for the Collins asymmetries from a deuteron target, that are consistent with zero, within statistics [42]. We note that the Collins function may also be determined separately from an azimuthal asymmetry in e^+e^- annihilation [43]. It was pointed out [35–37] that comparisons of DIS and the Drell-Yan process will be particularly interesting: from the properties of the Wilson lines it follows that the Sivers functions relevant in DIS and in the Drell-Yan process have opposite sign, violating universality of the distribution functions. This process dependence is a unique prediction of QCD. It is entirely calculable and awaits experimental testing. For work on the process (in)dependence of the Collins function, see [37,44]; recent model calculations of the function in the context of the gauge links may be found in [41,45].

A single-spin asymmetry in $p\,p$ scattering was identified recently [46] that also belongs to the class of "leading-power" observables and may give access to Sivers functions. The reaction considered was the inclusive production of jet pairs, $p\,p^{\uparrow} \rightarrow \text{jet}_1\,\text{jet}_2\,\text{X}$, for which the two jets are nearly back-to-back when projected into the plane perpendicular to the direction of the beams, which is equivalent to the jets being separated by nearly $\Delta\phi \equiv \phi_{j_2} - \phi_{j_1} = \pi$ in azimuth. This requirement makes the jet pairs sensitive to a small measured transverse momentum, and hence allows the single-spin asymmetry for the process to be of leading power. The basic idea is very simple. The Sivers function represents a correlation of the form $\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}^{\perp})$ between the transverse proton polarization vector, its momentum, and the transverse momentum of the parton relative to the proton direction. In other words, if there is a Sivers-type correlation then there will be a preference for partons to have a component of intrinsic transverse momentum to one side, perpendicular to both $\boldsymbol{S}_T$ and $\boldsymbol{P}$. Suppose now for simplicity that one observes a jet in the direction of the proton polarization vector, as shown in Fig. 11. A "left-right" imbalance in $\boldsymbol{k}^{\perp}$ of the parton will then affect the $\Delta\phi$ distribution of jets nearly opposite to the first jet and give the cross section an asymmetric piece around $\Delta\phi = \pi$. The spin asymmetry A_{N} for this process will extract this piece and give direct access to the Sivers function. In contrast to SIDIS, it is rather sensitive to the nonvalence contributions to the Sivers effect, in particular the *gluon* Sivers function [46].

Figure 12 shows some predictions for the spin asymmetry in this reaction. Since nothing is known about the size of the gluon Sivers function, some simple models were made for it [46], based on earlier studies of [47] for the valence quark Sivers distributions. For details, see [46]. One can see that sizable asymmetries are by all means possible. Near $\delta\phi = \Delta\phi - \pi = 0$, however, gluon radiation is kinematically inhibited, and the standard cancelations of infrared singularities between virtual and real diagrams lead to large logarithmic remainders in the partonic hard-scattering cross sections. It is possible to resum these Sudakov logarithms to all orders in α_s. This was done at the level of leading logarithms in [46], for both the numerator and the denominator of the asymmetry. As the analysis revealed, Sudakov effects lead to a significant suppression of the asymmetry, as is also visible from the solid lines in Figure 12. This finding does not necessarily mean, however, that the asymmetry must be small, since as we pointed out before, the gluon Sivers function is entirely unknown and could well be larger than in the models assumed for Fig-
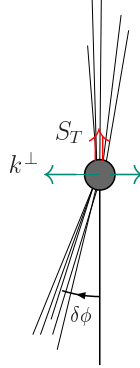

Figure 11. Asymmetric jet correlation. The proton beams run perpendicular to the drawing.
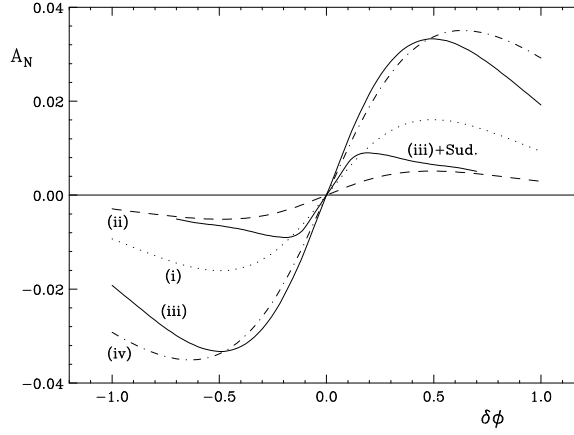
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Figure 12. Predictions [46] for the spin asymmetry A_N for back-to-back dijet production at RHIC, for various different models for the gluon Sivers function. Note that $\delta\phi = \Delta\phi - \pi = 0$, where $\Delta\phi$ is the azimuthal separation of the jets. The solid line marked as "(iii)+Sud." shows the impact of leading logarithmic Sudakov effects on the asymmetry curve (iii).

ure 12. In any case, any sign in experiment of a back-to-back asymmetry will be definitive evidence for the Sivers effect. We note that for the back-to-back dijet distribution, the issue of whether or not factorization occurs still remains to be investigated.

Originally, the Sivers function was proposed [33] as a means to understand and describe the significant single-spin asymmetries A_N observed [48] in $p^{\uparrow}p \to \pi X$, with the pion at high $p_\perp$. These are *inclusive* "left-right" asymmetries and may be generated by the Sivers function from the effects of the quark intrinsic transverse momentum $k_\perp$ on the partonic hard-scattering which has a steep $p_\perp$ dependence. The resulting asymmetry A_N is then power-suppressed as $\sim \langle k_\perp \rangle / p_\perp$ in QCD, where $\langle k_\perp \rangle$ is an average intrinsic transverse momentum. Similar effects may arise also from the Collins function. Fits to the available A_N data have been performed [49], assuming variously dominance of the Collins or the Sivers mechanisms. An exciting new development in the field is that the STAR collaboration has presented the first data on $p^{\uparrow}p \to \pi X$ from RHIC [50]. The results are shown in Fig. 13. As one can see, a large A_N persists to these much higher energies. Fig. 13 also shows predictions based on the Collins and the Sivers effects [49], and on a formalism [51,52] that systematically treats the power-suppression of A_N in terms of higher-twist parton correlation functions (for a connection of the latter with the Sivers effect, see [37]). The STAR data clearly give valuable information already now. For the future, it will be important to extend the measurements to higher $p_\perp$ where the perturbative-QCD framework underlying all calculations will become more reliable. We note that STAR has also measured the unpolarized $pp \to \pi^0 X$ cross section in the same kinematic regime, which shows very good agreement with NLO pQCD calculations [50]. We note that the general consistency of RHIC $pp \to \pi^0 X$ data with NLO pQCD results, already seen in Fig. 4, is in contrast to what was observed at lower energies in the fixed-target regime [53].
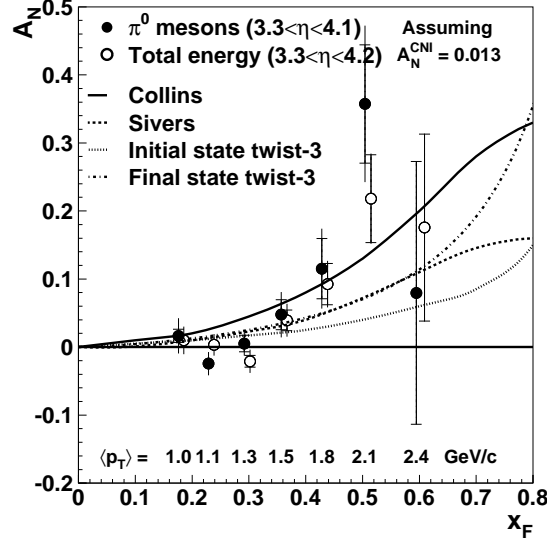
Figure 13. Recent STAR results for the asymmetry A_N in $pp \to \pi^0 X$ in the forward Feynman-x_F region [50].

3.4 Two other developments

It was recognized some time ago that certain Fourier transforms of generalized parton densities with respect to transverse momentum transfer give information on the position space distributions of partons in the nucleon [54]. For a transversely polarized nucleon, one then expects [55] a distortion of the parton distributions in the transverse plane, which could provide an intuitive physical picture for the origins of single-spin asymmetries.

Finally, *double*-transverse spin asymmetries A_TT in pp scattering offer another possibility to access transversity. Candidate processes are Drell-Yan, prompt photon, and jet production. Recently, the NLO corrections to $p^\uparrow p^\uparrow \to \gamma X$ have been calculated [56]. The results show that A_TT is expected rather small at RHIC. It has also been proposed [57] to obtain transversity from the double-spin asymmetries A_TT in Drell-Yan and J/ψ production in possibly forthcoming polarized $\bar{p}p$ collisions at the GSI. An advantage here would be the fact that valence-valence scattering is expected to dominate. On the other hand, the attainable energies may be too low for leading-power hard-scattering to clearly dominate.

14

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16